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Strategic Storages of Gas in Salt Layers and Creep and Overburden Effects on Volume Loss

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ABSTRACT

The demands for fossil fuels such as natural gas, oil and other hydrocarbon products have been raised in recent decades. Supplying these demands during peak period highlights the importance of storing energy resources during the production. Concerning this issue, storing gas in salt caverns is a suitable method. To describe the mechanical behavior of a typical rock salt due to creep phenomenon, the Multi-mechanism Deformation (MD) creep constitutive model is implemented into the Ansys finite element package using a Fortran routine. To investigate the creep effect on the structural response and volume shrinkage of a salt cavern, an implicit creep analysis is conducted under cyclic loads. The results reveal that applying the overburden pressure leads to a more volume shrinkage of the cavern, while placing overburden layer itself over the salt layer instead of the overburden pressure results in the lower volume shrinkage. Finally, using the contact element between the overburden layer and the salt layer, the volume shrinkage will decrease even further.

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1. Introduction

Regarding the pivotal role of the fossil fuels to meet the demands for energy in the recent decades, the studies on method by which the fuels are stored have been conducted. In general, different methods are utilized to store natural gas including depleted reservoir, salt cavern and aquifer.

To store hydrocarbons including the natural gas, petroleum and ethylene, the salt cavern is a suitable choice. It is more germane to short-term storage owing to the great deliverability which means it facilitates the rapid changing from the injection phase to the withdrawal [1].

As pioneer, Canada used underground salt caverns, to store the hydrocarbons in the early World War II. On account of the Suez Crisis, Britain made use of these structures to store the crude oil. Ten years later, the United States and Canada managed to store gas using these caverns [1]. Numerous studies have been conducted in which rock salt mechanical behavior and other related issues have been investigated as given in the below.

Cristescu, in 1993, suggested a constitutive equation for rock salt to describe transient and steady creep, volumetric dilatancy/ compressibility, and the long-term failure. Moreover, a new method applied to determine the visco-plastic potential for steady creep based on laboratory data [2]. In a study, Weatherby et al, in 1996, using some numerical techniques to incorporate multi-mechanism deformation (MD) creep model for rock salt into the JAC3D numerical package, in which creep equations integration was based on Forward Euler method, show that the MD creep model can be used in 3D FEM modeling [3].

Jin and Cristescu, in 1998, introduced an elastic-viscoplastic equation describing the transient creep based on the results of tri-axial tests on the Gorleben rock salt. The model fitting well with lab data, was incorporated into the VISCO finite element software [4]. In 1999, Yang et al. studied the creep behavior of rock salt by examining quantitatively the effects of axial and confining pressure on the time-dependent stress-strain behavior of rock salt based on the several uniaxial and tri-axial compression tests. It is worth mentioning that time hardening and strain hardening effects were investigated [5].

Heuserman et al, in 2003, using the LUBBY2 creep model, including transient and steady creep, conducted a nonlinear finite element analysis to study the underground salt cavern. Moreover, usability and stability criteria of caverns in some examples were studied [6]. Wang et al., in 2013, presented a new designing procedure for shapes of salt caverns in which the cavern is divided into the upper structure and the lower one. The paper reveals that the maximum pressure determines the shape of the lower structure, while the minimum determines the shape of the upper one. The offered method shows better results regarding volume reduction, plastic volume rate, displacement and etc. [7]. Nazary Moghadam et al. also, in 2013, using an elasto-viscoplastic creep model considering short and long-term failure along with the rock salt dilatancy behavior, performed a numerical simulation of underground cavern during the transient and steady creep. Implementing Lagrangian finite element formulation, the variation of stress and large deformations of the cavern were applied in the creep model [8].

In 2013, Xie and Tao investigated the rock salt creep deformations in drilling applications. Incorporating the MD model in the Abaqus finite element software, drilled boreholes closure and ovalization amount of the casing while drilling were examined [9].

In 2015, Thoraval et al. suggested a generic model predicting long-term behavior of salt caverns after the operating period, which may work as a risk evaluation procedure, and gave some quantitative details concerning the abandoned caverns evolution according to numerical modeling and the consequences affecting the cavern after the operating period. Besides, the proposed model reveals that the brine surplus pressure increase in the cavern ends in the walls to be damaged [10].

In a study in 2016, K. Khaledi et al. using the Lubby2 creep constitutive model and implementing it into the Code-bright finite element package, simulated a salt cavern creep behavior. A global sensitivity analysis investigating the material parameters influence on the mechanical response of salt cavern, and an inverted analysis, based on synthetic data, determining the material parameters of the model were carried out accounting for the Metamodeling technique to lessen the computational time [11].

In the current study, the goal is to examine effect of overburden layer placed over salt layer and contact elements used between the salt layer and overburden layer, on the volume loss of a salt cavern and make a comparison to the case in which an equivalent overburden load is applied. To this purpose, the MD constitutive equations are implemented into the Ansys (APDL) using the usercreep.f routine considering the implicit creep method. Then, the Ansys verification is conducted by a direct comparison between a clean rock salt tri-axial test results and those obtained from FEM analysis in the Ansys. Next, a typical salt cavern under operating loads or cyclic loads and using the implicit creep method is analyzed. Finally, in three different cases, the numerical results such as horizontal displacements, vertical displacements and volume reduction, will be presented and compared.

2. Multi-Mechanism Deformation (MD) Creep Model Equation

In the current paper, the MD creep model suggested by Munson and Dawson in 1984 [3], was utilized to incorporate in the Ansys The model is a simpler form of the MDCF* model, suggested by Chan et al. [12], which considers tensile and shear damages as well as healing characteristics of the rock salt during the creep.

*. Multi-mechanism Deformation Coupled Fracture

Assuming no damage and healing in rock salt and focusing on the overburden layer effect on deformations of the cavern and the numerical difficulty of MDCF implementation in the commercial codes, the MD model was chosen to be implemented.

The MD model in which transient and steady creep are described includes the dislocation climb mechanism at high temperatures and low stresses, an unknown mechanism occurring at low temperatures and low stresses, and a dislocation slip mechanism at high stress. Thus creep rate constitutive relations are written as:

$$\dot{\varepsilon}_{s_1} = A_1 \exp\left(-\frac{Q_1}{RT}\right)\left(\frac{\sigma_e}{\mu}\right)^{n_1} \tag{1}$$

$$\dot{\varepsilon}_{s_2} = A_2 \exp\left(-\frac{Q_2}{RT}\right)\left(\frac{\sigma_e}{\mu}\right)^{n_2} \tag{2}$$

$$\dot{\varepsilon}_{s_3} = H(\sigma_e - \sigma_0)\left(B_1 \exp\left(-\frac{Q_1}{RT}\right) + B_2 \exp\left(-\frac{Q_2}{RT}\right)\right) \sinh\left(\frac{q(\sigma_e - \sigma_0)}{\mu}\right) \tag{3}$$

where A_1, A_2, B_1 and B_2 are structural factors; Q_1 and Q_2 represent energies of activation; T and R are the absolute temperature and the universal gas constant, respectively. Moreover, n_1 and n_2 are stress power. Also, σ_e is the equivalent stress; σ_0 represents the stress limit of the dislocation slip mechanism; q and μ are stress constant and the shear modulus, respectively. It is worth mentioning that H is a Heaviside function. The steady creep rate, ε_s is equal to the summation of the creep rates including ε_{s1} representing the dislocation climb mechanism, ε_{s2} showing an undefined mechanism and ε_{s3} denotes the dislocation slide mechanism.

$$\dot{\varepsilon}_s = \dot{\varepsilon}_{s_1} + \dot{\varepsilon}_{s_2} + \dot{\varepsilon}_{s_3} \tag{4}$$

The F function, which is of branches

including; workhardening, equilibrium and recovery, is multiplied by steady creep rate to consider the transient creep effect and to obtain total creep rate, as written:

$$\dot{\varepsilon} = F * \dot{\varepsilon}_s \quad (5)$$

$$F = \begin{cases} \exp\left(\left[1 - \frac{\zeta}{\varepsilon_t^*}\right]^2 \Delta\right) & \zeta < \varepsilon_t^* \\ 1 & \zeta = \varepsilon_t^* \\ \exp\left(-\left[1 - \frac{\zeta}{\varepsilon_t^*}\right]^2 \delta\right) & \zeta > \varepsilon_t^* \end{cases} \quad (6)$$

where Δ and δ are functions representing hardening and recovery, respectively; ε_t^* indicates the transient strain limit and ζ represents the hardening which is obtained using integration of evolution rate equation as given:

$$\dot{\zeta} = (F-1)\dot{\varepsilon}_s = \dot{\varepsilon} - \dot{\varepsilon}_s \quad (7)$$

$$\Delta = \alpha_\omega + \beta_\omega \log\left(\frac{\sigma_e}{\mu}\right) \quad (8)$$

$$\delta = \alpha_r + \beta_r \log\left(\frac{\sigma_e}{\mu}\right) \quad (9)$$

$$\varepsilon_t^* = K_0 \exp(cT)\left(\frac{\sigma_e}{\mu}\right)^m \quad (10)$$

where, α_ω , β_ω , α_r , β_r , K_0 , c and m are the creep parameters. Implementation of the MD creep equations into the Ansys has been bone by the means of usercreep.f routine considering implicit creep. Since Ansys uses von Mises equivalent stress, it is used instead of the Tresca one in the MD model. The von Mises equivalent stress, which σ_i (i=1,2,3) denote principal stresses, is written as [13]:

$$\sigma_e = \sqrt{\frac{1}{2}[(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2]} \quad (11)$$

3. Verification of The Modified Usercreep.F Subroutine

A clean rock salt cylinder of radius 50mm and length 200mm, as shown in Figure. 1, is subjected to a tri-axial test at 25 °C. The hydrostatic stress and the deviatoric stress on the cylinder are is 15MPa and 11.5MPa, respectively. The elastic and creep properties for the WIPP clean rock salt are given in Table 1.

Table 1. The WIPP clean rock salt elastic and creep constants [3].

Elasticity	
E	31000 GPa
ν	0.25
μ	12400 GPa
ρ	2300 (kg/m³)
Creep	
A_1	8.386 e22 (1/sec)
Q_1	1.045 e5 (J/mol)
n_1	5.5
B_1	6.086 e6 (1/sec)
A_2	9.672 e12 (1/sec)
Q_2	4.180 e4 (J/mol)
n_2	5.0
B_2	3.034 e-2 (1/sec)
σ_0	20.57 MPa
q	5.335 e3
K_0	6.275 e5
m	3.0
c	0.009198 (1/K)
α_ω	-17.37
β_ω	-7.738
δ	0.58
R	8.3134

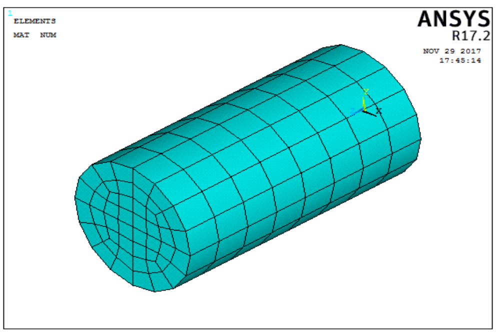


Figure 1. The rock salt cylinder-shaped sample finite element model in the Ansys.

A comparison has been made between the results of FEM creep analysis performed according to Table 2 with the experimental results as shown in (Figurer 2) The comparison indicates that the MD constitutive model fits well with empirical data.

Table 2. Loading conditions for tri-axial compression test of the rock salt at 25(°C) [14].

Stages	Load path	Deviatoric stress (MPa)	Hydrostatic stress (MPa)	Time (seconds)
(MPa)	Hydrostatic stress	0-11.5	15	30
(MPa)	Time	11.5	15	16 e6

4. Numerical Analysis of The Salt Cavern

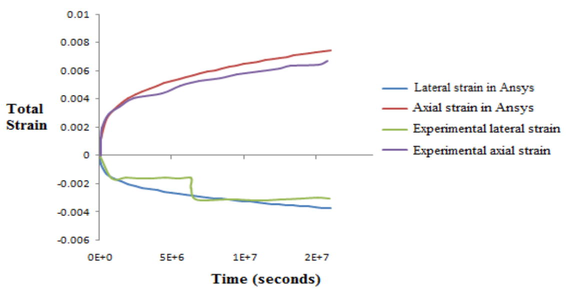


Figure 2. Comparison made between FEM creep analysis and experimental results.

In present paper, considering the effect of overburden layer and contact elements used at the interface of rock salt and the Clastic layer on salt cavern, FEM simulations of the cavern have been performed as follows:

- Clean rock salt layer with an overburden equivalent load
- Clean rock salt layer with Clastic overburden layer
- Clean rock salt layer with contact element and Clastic overburden layer

Assuming isotropic and homogeneous, the cavern which is axisymmetric would be simulated in 2D. In accordance with the normal operating period of the rock salt gas storages, analysis duration is about 946 million seconds or thirty years under cyclic operational loading as given in (Figure 3) In addition, transient analysis and large deformations effect have been considered in the creep analysis.

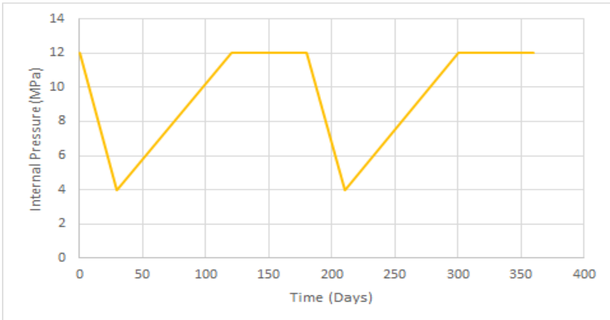


Figure 3. The salt cavern cyclic operational loading [9].

4.1. Salt Cavern with an Overburden Equivalent Load

An approximately cylinder-shaped salt cavern of radius 37.5m and height 233m is simulated at a cross section of rock salt of width 500m and height 800m as shown in Figure. 4. A 10MPa pressure load is imposed on the salt layer instead of the Clastic overburden layer and geo-static loading is applied as lateral loading. The salt layer is constrained on the axis of symmetry along x-direction and on the bottom of the salt layer along y-direction. The creep constants of a WIPP clean rock salt are presented in Table 1. It should be noted that the temperature is assumed to be 100°C for the creep analysis. The initial and boundary conditions are given as follows:

Boundary conditions:

$$\begin{cases} \sigma_{yy} = \sigma_v & y = H, \quad 0 < x < L \\ \sigma_{xx} = \sigma_v + \rho g\,(\mathrm{H} - \mathrm{y})/10^6 & 0 < y < H, \quad x = L \\ u_x = 0 & 0 < y < H, \quad x = 0 \\ u_y = 0 & y = 0, \quad 0 < x < L \end{cases}$$

Initial conditions:

$$\begin{cases} \sigma_{xx} = \sigma_{yy} = \sigma_{zz} = \sigma_v + \rho g\,(H - y)/10^6 & 0 < y < H, 0 < x < L \\ u_x = u_y = u_z = 0 & 0 < y < H, 0 < x < L \end{cases}$$

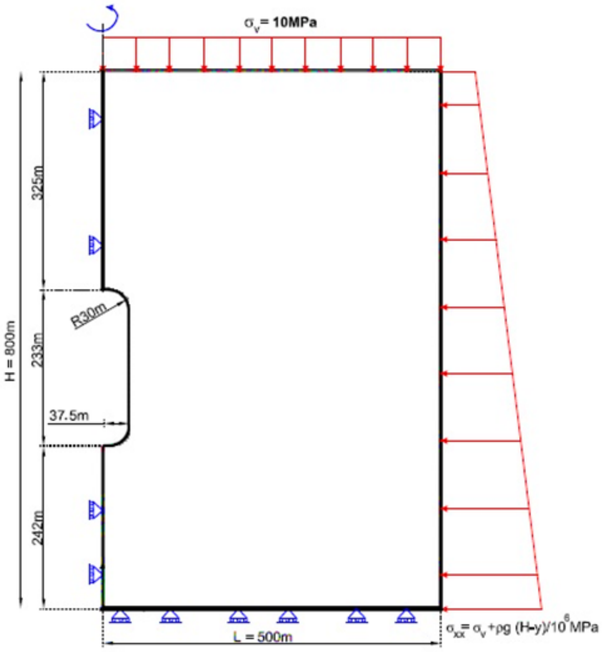


Figure 4. Clean rock salt layer with an equivalent overburden load [11].

4.2. Salt Cavern with Clastic Overburden Layer

In this situation in lieu of the equivalent load, the Clastic overburden of 500m thick is located on the salt layer, while there is no contact element application (Figure 5). The Clastic rock properties are presented in Table 3.

Table 3. The mechanical properties of Clastic overburden [15].

Material	Clastic
Bulk modulus (K) (MPa)	13300
Shear modulus (G) (MPa)	8000
Density (kg/m^3)	2000
Cohesion (MPa)	15
Friction angle (degree)	35

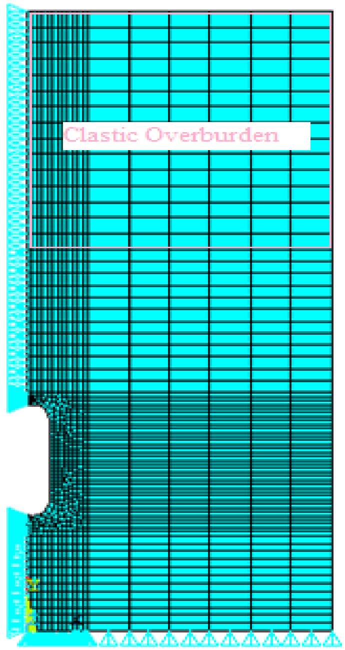


Figure 5. FEM mesh of the rock salt layer and the Clastic overburden layer.

4.3. Salt Cavern with Overburden Layer and Contact Element

In the current case, using node-to-surface contact type, the surface contact elements including CONTA175 and TARGE169 are applied between the Clastic and the rock salt layer. The Poisson's ratio and modulus of elasticity are obtained as given in the below:

$$\frac{2G}{3K} = \frac{1 - 2\upsilon}{1 + \upsilon} \quad \text{we have:} \quad \upsilon = 0.25$$

And also: $E = 3K(1\text{-}2\upsilon) = 19950$ MPa

5. Numerical Results

The results presented in this section cover the vertical and horizontal displacement distributions and volume loss. Furthermore, a comparison has been made for the three distinct cases and the results will be discussed.

In Figure. 6, it is evident that the bottom parts of the wall of cavern would face more horizontal displacement, which could be due to the fact that geostatic load and the self-weight effect of the salt and overburden layers increase as depth increases.

Moreover, the horizontal displacement distribution of the bottom and the roof of the cavern seems to be approximately the same which means the relative displacement of the bottom and the roof is trivial because there are horizontal constraints due to axial symmetry of the considered cavern.

Comparing the horizontal displacement distributions presented in Figure. 6(c)-(b), it is observed that the contact elements would affect the horizontal displacement distribution, i.e. applying contact elements leads to less horizontal displacements. Also, comparing Figure. 6(a) with two former cases, it is seen that the horizontal displacement would be more in this case.

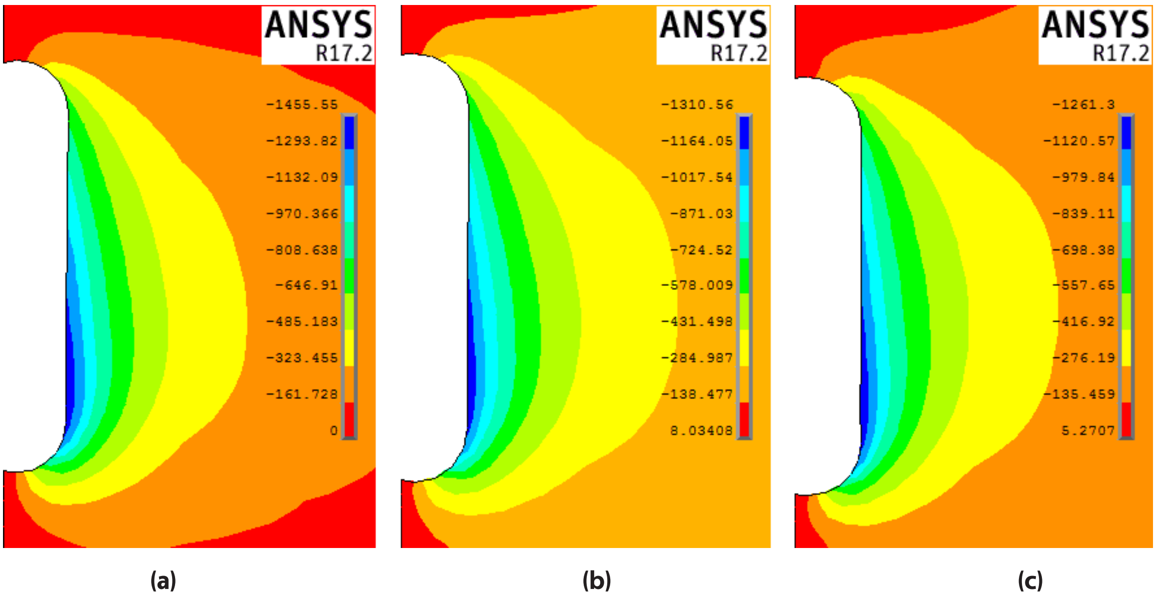
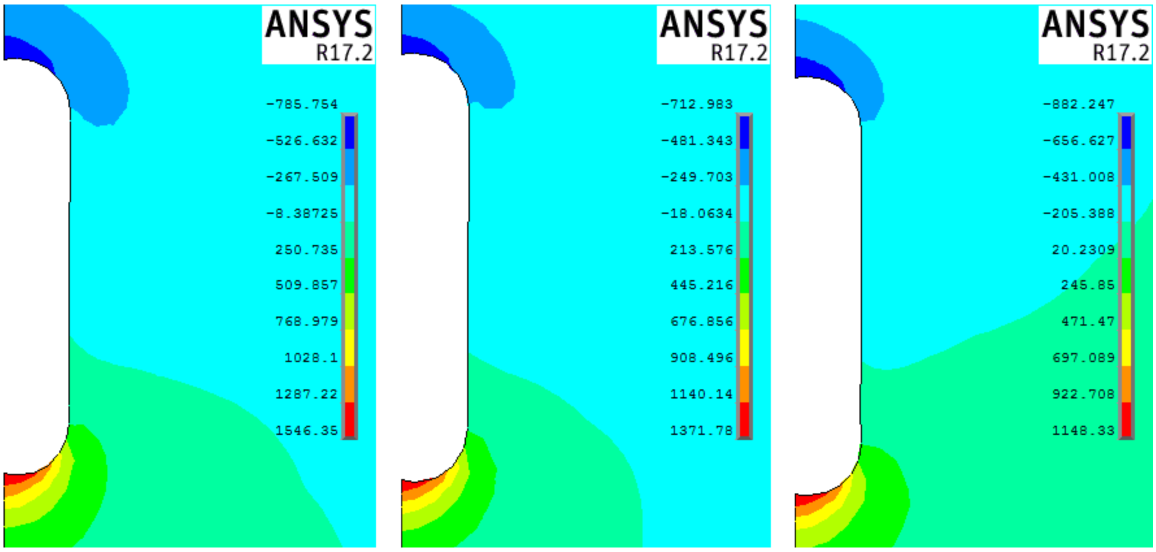


Figure 6. The distribution of horizontal displacement around salt cavern. (a) Salt cavern structure with equivalent overburden load, (b) Salt cavern with Clastic overburden layer, (c) Salt cavern with Clastic overburden layer and contact element.

Figure. 6. The distribution of horizontal displacement around salt cavern. (a) Salt cavern structure with equivalent overburden load, (b) Salt cavern with Clastic overburden layer, (c) Salt cavern with Clastic overburden layer and contact element.

It can be perceived in Figure. 7 that parts adjoining the roof of the cavern has negative which could be related to weight of the overburden and the salt layer. Besides, it is evident that the vertical displacements in parts next to the cavern bottom would be positive that may arise from the contributory factors, including lateral geostatic loading, the Clastic overburden and the rock salt weight along with the vertical and the horizontal reaction restrictions, leading to cavern bottom to move up along vertical axis. Comparing the roof and bottom of the cavern as shown in Figure. 7(a)-(b), reveals that vertical displacement at the bottom is roughly two times the roof, which may be owing to more strain at the bottom of cavern. On the other hand, as shown in Figure. 7(c), the bottom vertical displacement is around 1.3 times the roof indicating that the application of contact elements lessens the proportion.

Comparing vertical displacement distribution in two cases as shown in Figure. 7(b)-(c), it seems that in the case (b) vertical displacement at the cavern roof is almost 24% less and at the cavern bottom is 16% more than those of the case (c), however compared with the case (a) with no applied overburden layer, as shown in Figure. 7(a), it can be concluded that distance between the bottom and the roof of the cavern has decreased more in this case meaning that it may show larger volume loss.



(a) (b) (c)

Figure 7. The distribution of vertical displacement around salt cavern. (a) Salt cavern structure with equivalent overburden load, (b) Salt cavern with Clastic overburden layer, (c) Salt cavern with Clastic overburden layer and contact element.

Extracting to the nodal displacements of FEM creep analysis, the volume the salt cavern has been obtained for 30 years of operation. According to Table 4, the cylinder-shaped cavern initial volume is approximately 953581.7m^3. In case (a), imposing an equivalent overburden load on the salt layer, the cavern final volume reaches 888316.1m^3. In case (b), applying Clastic overburden layer on the salt layer, the volume of the cavern would be 894060.1m^3. Lastly, in case (c), implementing the contact elements on the interface of the Clastic and the salt layers, the volume reaches 895260m^3. Note that implementing the contact elements, the volume loss of the cavern was reduced to 1200 m^3.

Table 4. Volume loss of the underground salt cavern after 30 years.

	Initial volume (m^3)	Final volume (m^3)	Volume loss (m^3)
Case (a)	953581.6987	888316.1	65265.5987
Case (b)	953581.6987	894060.1	59521.5987
Case (c)	953581.6987	895260.03	58321.6687

6. Conclusions

In the current research, applying the overburden layer and contact elements and considering creep effect, thru implementing MD creep constitutive model into Ansys to carry out FEM creep analysis, on the horizontal and vertical displacements as well as volume loss of a typical salt cavern were investigated in three different cases. The more important results are given in the below:

- C It is observed that the horizontal displacement distribution in case (b) and (c) is less than that of salt cavern with an equivalent overburden load in case (a).
- Comparing the vertical displacement distribution of roof and the bottom of the cavern, in case (a) and case (b), it is seen that the cavern bottom vertical displacement is

nearly 2 times the cavern roof, but, in the case (c), the bottom to roof displacement ratio is almost 1.3 demonstrating that applying contact elements decreases the ratio.

- The volume losses are equal to $65265.6m^3$, $59521.6m^3$ and $58321.7m_3$ in case (a), case (b) and case (c), respectively, indicating overburden layer and the contact elements effect which resulted in less estimation of volume loss as a result of the creep predicting more life for the salt cavern gas storage.

7. References

1. T. Wang, C. Yang, X. Yan, and J. J. K. Daemen, (2015). Allowable pillar width for bedded rock salt caverns gas storage. J. Pet. Sci. Eng., vol. 127, pp. 433-444.
2. N. D. Cristescu, (1993). A general constitutive equation for transient and stationary creep of rock salt. Int. J. Rock Mech. Min. Sci. Geomech. Abstr., vol. 30, no. 2, pp. 125-140..
3. J. R. Weatherby, D. E. Munson, and J. G. Argüello, (1996). Three-dimensional finite element simulation of creep deformation in rock salt. Eng. Comput. Int J Comput.-Aided Eng., vol. 13, pp. 82-105.
4. J. Jin and N. D. Cristescu, (1998). An elastic/ viscoplastic model for transient creep of rock salt. Int. J. Plast., vol. 14, no. 1, pp. 85-107.
5. C. Yang, J. J. K. Daemen, and J.-H. Yin, (1999). Experimental investigation of creep behavior of salt rock. Int. J. Rock Mech. Min. Sci., vol. 36, no. 2, pp. 233-242.
6. S. Heusermann, O. Rolfs, and U. Schmidt, (2003). Nonlinear finite-element analysis of solution mined storage caverns in rock salt using the LUBBY2 constitutive model. Comput. Struct., vol. 81, no. 8, pp. 629-638.
7. T. Wang, X. Yan, H. Yang, X. Yang, T. Jiang, and S. Zhao, (2013). A new shape design method of salt cavern used as underground gas storage. Appl. Energy, vol. 104, pp. 50-61.
8. S. Nazary Moghadam, H. Mirzabozorg, and A. Noorzad, (2013). Modeling time-dependent behavior of gas caverns in rock salt considering creep, dilatancy and failure. Tunn. Undergr. Space Technol., vol. 33, pp. 171-185.
9. J. Xie, Tao Gang, (2013). Modeling and Analysis of Salt Creep Deformations in Drilling Applications. SIMULIA, community conference, Vienna, Austria.
10. A. Thoraval, F. Lahaie, B. Brouard, and P. Berest, (2015) .A generic model for predicting long-term behavior of storage salt caverns after their abandonment as an aid to risk assessment. Int. J. Rock Mech. Min. Sci., vol. Complete, no. 77, pp. 44-59.
11. K. Khaledi, E. Mahmoudi, M. Datcheva, D. König, and T. Schanz, (2016). Sensitivity analysis and parameter identification of a time dependent constitutive model for rock salt. J. Comput. Appl. Math., vol. 293, pp. 128-138.
12. K. Chan, S. Bodner, D. E. Munson, and A. Fossum, (1996). A Constitutive Model for Representing Couple Creep, Fracture, and Healing in Rock Salt. Presented at the Proceedings, 4th Conf. on the Mech. Behavior of Salt, pp. 221-234.
13. Ansys Material Reference. Ansys Inc., 2017.
14. K. D. Mellegard and T. W. Pfeifle, (1993). Creep tests on clean and argillaceous salt from the Waste Isolation Pilot Plant. Sandia National Labs., RE/SPEC, SAND--92-7291.
15. M. S. Bruno and Gas Research Institute, (2005). Geomechanical analysis and design considerations for thin-bedded salt caverns: final report. Arcadia, CA: Terralog Technologies USA.

مخازن استراتژیک گاز در لایه های نمک و اثرات خزش و سربار بر کاهش حجم

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چکیــــــده

تقاضا برای سوخت های فسیلی مانند گاز طبیعی، نفت و دیگر محصولات هیدروکربنی در دهه های اخیر افزایش یافته است. پاسخ گویی به این تقاضا در دوره اوج مصرف، اهمیت ذخیره سازی منابع انرژی را در دوره تولید نشان می دهد. در ارتباط با این موضوع، ذخیره کردن گاز در حفره های نمکی روش مناسبی است. برای توصیف رفتار مکانیکی یک سنگ نمک عادی بر اثر پدیده خزش، مدل ساختاری خزش تغییرشکل دارای چند مکانیزم (MD) در نرم افزار اجزا محدود ANSYS با استفاده از یک روتین Fortran گنجانده شد. جهت بررسی اثر خزش بر پاسخ سازه ای و کاهش حجم یک حفره نمکی، تحلیل خزش ضمنی تحت بارهای چرخه ای انجام شد. نتایج نشان می دهد که اعمال بارهای فشاری سربار به کاهش حجم کمتری در حفره نمکی می انجامد، در حالی که قراردادن خود لایه سربار بر لایه نمک بجای فشار سربار، کاهش حجم کمتری را در پی دارد. نهایتا، با استفاده از المان تماس بین لایه سربار و لایه نمک کاهش حجم، کمتر هم خواهد بود..

واژگان کلیدی: حفره نمکی، مدل خزش MD، سنگ نمک، خزش ضمنی، کاهش حجم، بارگذاری چرخه ای